

Submillimetre observations of RX J1856.5–3754^{*}

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ABSTRACT

We report on submillimetre bolometer observations of the isolated neutron star RX J1856.5–3754 using the LABOCA bolometer array on the Atacama Pathfinder Experiment (APEX) Telescope. No cold dust continuum emission peak at the position of RX J1856.5–3754 was detected. The 3σ flux density upper limit of 5 mJy translates into a cold dust mass limit of a few earth masses. We use the new submillimetre limit, together with a previously obtained H-band limit, to constrain the presence of a gaseous, circumpulsar disc. Adopting a simple irradiated-disc model, we obtain a mass accretion limit of $\dot{M} \lesssim 10^{14} \text{ g s}^{-1}$, and a maximum outer disc radius of $\sim 10^{14} \text{ cm}$. By examining the projected proper motion of RX J1856.5–3754, we speculate about a possible encounter of the neutron star with a dense fragment of the CrA molecular cloud a few thousand years ago.

Key words: submillimetre- stars: neutron- X-rays: individual: RX J1856.5–3754

1 INTRODUCTION

Since the discovery of planets around the pulsar PSR 1257+12 by Wolszczan & Frail (1992), dusty discs around pulsars have become interesting to observers, who have been trying to detect them in the infrared (IR) or at (sub-)millimeter wavelengths. Most comprehensive are the searches by Löhmer et al. (2004) and Greaves & Holland (2000). Previous searches had concentrated mainly on recycled, thus formerly accreting, radio pulsars as the most likely objects to be surrounded by dusty discs. Neither of the above mentioned surveys detected dust emission around the planet-hosting PSR 1257+12, nor did the recent search with *Spitzer* at $24 \mu\text{m}$ and at $70 \mu\text{m}$ by Bryden et al. (2006). However, dusty discs could also be present around non-recycled neutron stars (NSs). Following the supernova explosion, which creates the NS, some of the explosion ejecta may fail to escape and remain bound - forming a fallback disc. Such fallback discs are a general prediction of current supernova models (Michel & Dessler 1981; Chevalier 1989), and have been invoked by a number of authors to explain a variety of phenomena related to NSs (e.g., Chatterjee et al. 2000; Alpar 2001; Menou et al.

2001; Blackman & Perna 2004). Recently, Wang et al. (2006) reported the discovery of mid-infrared emission from a cool disc around the Anomalous X-ray pulsar AXP 4U 0142+61. Wang et al. (2006) interpreted their detection as a passive disc, while Ertan et al. (2007) argued that it could also originate from an actively accreting disc. To date, AXP 4U 0142+61 is the only isolated neutron star for which a fallback disc is believed to have been detected. Such discs appear to be rare. According to Ekşi & Alpar (2005) fallback disc are rare because they are likely to be disrupted when the newly born NS spins rapidly through the propeller stage, at which in-flowing matter, instead of being accreted, would be expelled. The fallback discs can survive if the initial NS spin is slow enough ($\geq 40 \text{ ms}$ at a magnetic moment of $\mu = 10^{30} \text{ G cm}^3$). Jones (2007) studied the effect of pulsar wind induced ablation of fallback discs. He concluded that long-lived discs could be present in many pulsars without exceeding published limits on IR luminosity.

In the following, we report on submillimetre observations of RX J1856.5–3754, which is the brightest and closest member of a class of NSs neglected so far in the search for circumstellar discs, the X-ray thermal isolated neutron stars. They are peculiar because they show pure thermal soft X-ray spectra without any (confirmed) non-thermal emission, especially no confirmed radio emission; for reviews, see Kaplan (2008) or Haberl (2007). These objects

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have periods in the range of 4 to 12 s. Thus, they are much slower than the bulk of radio pulsars. Their X-ray pulse periods and period derivatives are similar to those of the AXPs and soft gamma-ray repeaters, SGRs, (see, e.g., Kaplan & van Kerkwijk 2009). This has led to discussions about whether they may be related to those objects. For example, Alpar (2001, 2007) suggested that the X-ray thermal isolated NSs may simply have accretion discs with smaller masses than those of the AXPs. We note that it is currently not clear whether AXPs host accretion discs. The prevailing model for AXPs and SGRs is the magnetar model – isolated, young neutron stars with exceptionally high ($\approx 10^{14}$ G) surface magnetic fields (Duncan & Thompson 1992).

RX J1856.5–3754 has been observed at radio wavelengths (to date without detection), near infrared (without detection), optical and X-ray wavelengths. The striking absence of deviations from a pure blackbody in its X-ray spectrum has led to lively discussions on the nature of the object and of its X-ray emission, including highly magnetized atmospheres (e.g., Ho et al. 2007), condensed surfaces (e.g., Burwitz et al. 2003) and quark stars (e.g., Drake et al. 2002). The most recent, preliminary, parallax by Kaplan et al. (2007) is 167^{+18}_{-15} pc and marks RX J1856.5–3754 as one of the closest NSs currently known. Tiengo & Mereghetti (2007) discovered the ≈ 7 s pulsations of RX J1856.5–3754, which has an extremely small pulsed fraction in the 0.15–1.2 keV range of only 1.2 %. A timing study by van Kerkwijk & Kaplan (2008) inferred a magnetic field of 1.5×10^{13} G assuming spin-down by dipole radiation. Interestingly, the spin-down luminosity is not high enough to explain the H α nebula around RX J1856.5–3754, discovered by van Kerkwijk & Kulkarni (2001). The nature of the H α nebula remains unclear to date (see, e.g., van Kerkwijk & Kaplan 2008). These authors also derived a characteristic age of 4 Myrs, which is much older than the kinematic age, 0.5 Myrs, obtained assuming an origin in the Upper Scorpius OB association (e.g., Walter & Lattimer 2002). At such ages, any fallback disc around the source would be expected to be rather cool.

Within distance error bars, 117 ± 12 pc by Walter & Lattimer (2002) to 167^{+18}_{-15} pc by Kaplan et al. (2007), RX J1856.5–3754 appears to be in the outskirts of the Corona Australis star-forming cloud, whose distance is relatively well known: 129 ± 11 pc from the orbit solution of the double-lined spectroscopic binary TY CrA by Casey et al. (1998); for a detailed discussion we refer to Sect. 1.3 in Neuhäuser & Forbrich (2008). Bondi-Hoyle accretion (Bondi & Hoyle 1944; Bondi 1952) from the interstellar medium (ISM) is unlikely to be a major contributor to the observed X-ray luminosity today, given the high velocity of this neutron star (van Kerkwijk & Kulkarni 2001). Furthermore, it is likely that isolated NSs accrete at sub-Bondi rates (Perna et al. 2003). The accretion rate scales inversely with the magnetic moment as $\mu^{-2.1}$ according to Toropina et al. (2006); Romanova et al. (2003). RX J1856.5–3754 has a high magnetic field, 1.5×10^{13} G (van Kerkwijk & Kaplan 2008), reducing the possibility of accretion even further. However, as Drake & Marshall (2003) noted, RX J1856.5–3754 might have passed more

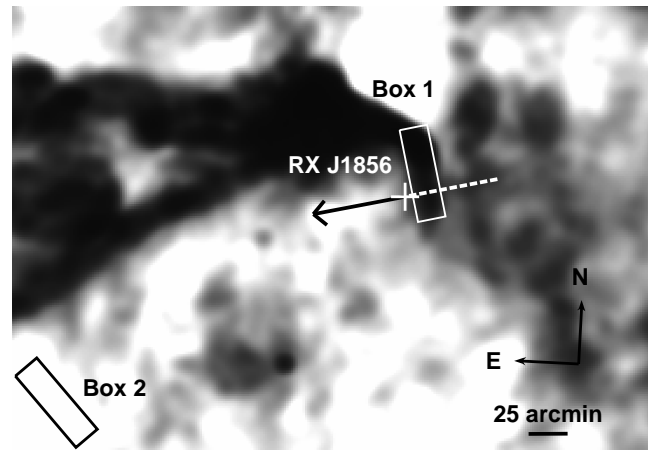


Figure 1. The IRAS/IRIS 100 μ m band of the neighbourhood of RX J1856.5–3754. Strong infrared emission, signaling the presence of dust, is shown by darker areas. The peak dust emission outlines the CrA star forming region. The position of RX J1856.5–3754, as well the direction of its proper motion, is indicated. The dashed white line shows the rough projection of the proper motion into the past. About 3000 years ago the neutron star might have crossed a region of the denser dust filament – depending on the actual distances of the filament and RX J1856.5–3754. The boxes 1 and 2 cover the same area, see section 4.3 for discussion.

dense regions than it now resides in. Indeed the IRAS 100 μ m image shows some cloud fragments projected along the past trajectory of RX J1856.5–3754 (see Fig. 1), opening the possibility that the neutron star collected material in the past.

Here, we investigate the surroundings of RX J1856.5–3754 for cold dust as one might expect either in an old fallback disc or in a dense gas disc. The gas content of a fallback disc is not well known. The formation from supernova ejecta would be expected to produce a disc mainly consisting of heavy elements. Currie & Hansen (2007) showed that gas from viscous, circumpulsar discs typically depletes on very short, $\approx 10^5$ yr, timescales due to high temperatures during the early evolutionary stages, subsequent rapid spread of the disc and cooling allowing for the heavy elements to condense onto grains. In addition, Phillips & Chandler (1994) have shown that for a pulsar moving with ≈ 100 km s $^{-1}$ through the ISM, small dust grains with radii of ≤ 0.1 μ m are spiraled in from a circumpulsar disc to the neutron star on a time scale of order 10^6 years. Thus, a circumpulsar disc at the age of RX J1856.5–3754 is likely to be similar to debris discs, which are dust-rich and dominated by larger grains (see, e.g., Krivov et al. 2009) as opposed to protostellar discs, which are gas-rich. If, on the other hand, RX J1856.5–3754 has collected new, gas-rich material from the outskirts of the Corona Australis star-forming cloud, the disc composition could more closely resemble a protostellar disc. Given the uncertainties in the gas content and composition of a possible disc around RX J1856.5–3754, we will consider here both types of discs – dense, gas-rich protostellar-type discs, and gas-poor, dust-rich debris-type discs.

2 OBSERVATIONS AND DATA REDUCTION

RX J1856.5–3754 was observed from the 18th to the 24th of April 2008 using the 295-element Large Apex Bolometer Camera (LABOCA, Siringo et al. 2009) on the Atacama Pathfinder Experiment (APEX) telescope (Güsten et al. 2006). LABOCA operates at 345 GHz ($870\mu\text{m}$) with a bandwidth of 60 GHz. The total on-source observing time was 18 hours. Mapping was performed on-the-fly using spiral patterns to ensure even coverage of the source. To obtain the lowest possible flux limit, the most sensitive part of the array was centered on the source. The observing conditions were good to excellent with precipitable water vapor levels typically below 0.5 mm. Sky-dips were performed hourly, and combined with radiometer readings to obtain accurate opacity estimates as described by Weiß et al. (2008). The absolute flux calibration follows the method outlined by Siringo et al. (2009), and is expected to be accurate to within $\approx 10\%$ (e.g., Greve et al. 2009). The nominal LABOCA beam is FWHM $18.6'' \pm 1.0''$, and the pointing uncertainty is $\sim 4''$. The data were reduced using the February 2008 release of the BoA reduction package² (Schuller et al. in prep.). Reduction steps included the removal of correlated (atmospheric and electronic) noise in several iterations, and the removal of spikes and excessively noisy channels.

In the second part of the last observation night, we found a sharp drop in the root mean square (rms) of individual bolometer time streams. As these time streams did not contain the expected correlated sky component, these observations (about two hours) were excluded from further consideration. To filter out extended emission and residual atmospheric noise at low frequencies, we used direct high-pass filtering of the raw time streams applying the fast Fourier transform (FFT). This was done by rejecting frequencies below a chosen cutoff, ν_C .

For each scan, a map with $3'' \times 3''$ sized pixels was constructed, weighting the data by the inverse rms of each reduced time stream. All maps were then co-added, and the final map was smoothed with the LABOCA beam, $18.6''$. The map rms per beam was computed as the pixel rms in the smoothed map, Fig. 2, applying the BoA-task `computeRms()`.

3 RESULTS

Fig. 2 is a filtered image, where all modes corresponding to spatial sizes larger than about $150''$ are filtered out (the median scan speed is around 96 arcsec s^{-1}). The same area as visible in Fig. 2 was considered when we computed the rms/beam for filtered or unfiltered maps. No submillimetre-emission has been found at or near the position of RX J1856.5–3754. The rms has been measured as 3.02 mJy/beam for the map obtained without direct FFT filter, and 1.49 mJy/beam for the direct-FFT-filtered map. Applying the filter on a test point source of 10 mJy results in recovering of 89 % of the original flux. We correct for this

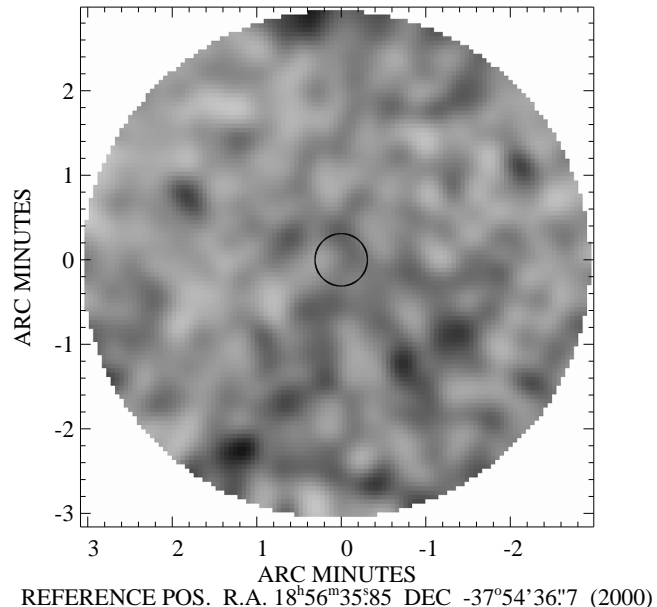


Figure 2. This LABOCA-345 GHz-continuum-map has been filtered for all modes corresponding to spatial sizes larger than about $150''$. Darker areas indicate higher submillimetre flux. The circle is centered on the position of RX J1856.5–3754 with a radius of $18.6''$ (double beam size). No obvious submillimetre point source has been detected at the position of RX J1856.5–3754. This map has a rms of 1.49 mJy/beam , corresponding to a 3σ flux density limit of 5 mJy (see text).

factor and obtain an 3σ limit of 5 mJy/beam for the filtered map of RX J1856.5–3754.

4 DISCUSSION

4.1 Dust mass limit

In contrast to infrared emission, submillimetre emission is nearly always optically thin and traces the total dust mass. The conventional formula for calculating this dust mass is:

$$M_d = \frac{F_\nu D^2}{B_\nu(T_d, \lambda) \kappa_\nu^d(\lambda)} \quad (1)$$

where ν is the frequency, F_ν is the flux density, D is the distance, B_ν is the Planck function at a dust temperature T_d , and κ_ν^d is the dust mass absorption coefficient.

The value of κ_ν^d depends on the grain parameters. As noted in the introduction, we consider in the following dust in protostellar discs as well as in debris discs to reflect the wide range of possible disc compositions around RX J1856.5–3754. Since the gas content in fallback discs is unconstrained, we calculate the dust mass limits for both disc types. The overall mass of a protostellar-composition disc would be larger by roughly a factor 100, the conventional gas-to-dust-ratio.

In the case of protostellar-disc dust, small grains are present. For such protostellar dust, we use $\kappa_\nu^d = 3 \text{ cm}^2 \text{ g}^{-1}$ according to the relation by Beckwith et al. (1990): $\kappa_\nu = 0.1(\nu/10^{12} \text{ Hz})^\beta \text{ cm}^2 \text{ g}^{-1}$ with $\beta = 1$, and where κ_ν is the opacity of dust and gas together. Beckwith et al. (1990) assumed a gas-to-dust-ratio of 100. Ossenkopf & Henning

¹ More on LABOCA calibration can be found at: <http://www.apex-telescope.org/bolometer/laboca/calibration/>

² <http://www.apex-telescope.org/bolometer/laboca/boa/>

Table 1. Dust mass limits for the measured 870 μm 3σ flux density limit of 5 mJy at different dust temperatures, T_d and mass absorption coefficients, $\kappa_{345\text{GHz}}^d$.

dust type	$\kappa_{345\text{GHz}}^d$ [$\text{cm}^2 \text{g}^{-1}$]	T_d [K]	M_d -limit [M_\oplus]
Protostellar	3	17	2.0
Debris disc	0.3	30	9.1
Debris disc	1.7	17	3.6
Debris disc	1.7	30	1.6
Debris disc	1.7	100	0.4

(1994) estimated uncertainties for ice-covered dust grains in protostellar molecular cloud cores to be usually within a factor of 5. In the case of debris discs, reported dust mass absorption coefficients at submillimetre wavelength range from $\kappa_{\nu}^d = 0.3 - 1.7 \text{ cm}^2 \text{g}^{-1}$ (Dent et al. 2000; Najita & Williams 2005).

Dust temperatures, T_d , can range from ≈ 10 K for cold interstellar dust to ≈ 1500 K (sublimation temperature of silicate dust). Due to missing constraints in the FIR we assume as a first approximation that the bulk of the dust visible at 870 μm emits at around 17 K. According to the X-ray irradiated disc model by Vrtilek et al. (1990), and with the X-ray luminosity of RX J1856.5–3754, $L_X = 8.8 \times 10^{31} \text{ erg s}^{-1}$ at a distance of $d = 167 \text{ pc}$ (Drake et al. 2002), this temperature is reached at a radius of $\approx 7 \times 10^{13} \text{ cm}$ from the neutron star. This value is within the disc sizes discussed in models of NS fallback discs, e.g., by Ertan et al. (2007). Dust in debris discs is thought to be warmer than the one in protostellar discs, with a range from 10 K up to a few hundred K, but mostly below 110 K (Wyatt 2008). In Table 1 we give dust mass limits for the different sets of parameters.

Another uncertainty of the mass estimation is related to the porosity of the dust. Porous grains are expected both in the cold ISM as well as in debris discs. Their influence on κ_{ν}^d and T_d can result in masses of a factor three smaller with respect to masses derived for non-porous grains (Voshchinnikov et al. 2006). In case of fast-moving neutron stars like RX J1856, ‘sandblasting’ by particles from the ISM fragments the dust (Phillips & Chandler 1994) and reduces the number of porous grains.

4.2 Constraints on the presence of a gaseous disc component

If discs around isolated NSs are (still) gas-rich, they are expected to be emitting mostly in the IR and longer wavelengths. In the following we use the disc model by Perna et al. (2000) to constrain the presence and properties of a potential gaseous circumstellar disc around RX J1856. The model is based on an active, viscous disc, and takes irradiation through X-rays into account following the approach by Vrtilek et al. (1990). We note that the model does not include radiative transfer modeling, and it assumes that the disc is optically thick throughout. However, given our scarce knowledge about neutron star discs in general, and the lack of an actual IR or mm detection for RX J1856 we restrict to this model in the present work.

Given the very low X-ray luminosity of RX J1856 ($8.8 \times$

$10^{31} \text{ erg s}^{-1}$ at 167 pc, Drake et al. 2002), if there is an active disc, it must be in the propeller phase, which is equivalent to saying that the magnetospheric radius, $R_m = 6.67 \times \dot{M}/(10^{17} \text{ g s}^{-1}) \text{ cm}$, must be smaller than the corotation radius, $R_{co} = 1.5 \times 10^8 (P/s)^{2/3} \text{ cm}$, where P is the period of the X-ray pulsar. Therefore, in our modelling of the disc emission, the inner radius of the disc, set equal to R_m , is restricted to be smaller than R_{co} . With the magnetic field strength estimate $1.5 \times 10^{13} \text{ G}$ by van Kerkwijk & Kaplan (2008), this yields the condition that only accretion rate values $\dot{M} \lesssim 10^{16} \text{ g/s}$ are allowed (or else the star would be accreting and hence be much brighter in X-rays).

In addition to our submillimetre observations, we use previously acquired data at near-infrared and infrared wavelengths. More specifically, we use the H -band limit derived at the position of RX J1856, $H = 21.54 \pm 0.24 \text{ mag}$, corresponding to a flux density of 0.0025 mJy (Posselt et al. 2009). Furthermore, we derive the conservative IRAS/IRIS flux density limits at the position of the neutron star applying the IRIS atlas maps (Miville-Deschênes & Lagache 2005; Neugebauer et al. 1984). These limits, $< 1.9 \text{ Jy}$, $< 2.7 \text{ Jy}$, $< 2.4 \text{ Jy}$, and $< 9.6 \text{ Jy}$ at 12, 25, 60 and 100 microns respectively, are too large to constrain our model.

Within the allowed range of \dot{M} , we then investigated the expected disc emission as a function of \dot{M} , and the disc boundaries R_{in} and R_{out} . We find that R_{in} influences the emission at wavelengths shorter than the ones considered here, and therefore the model parameters that can be constrained are \dot{M} and R_{out} (assuming a typical disc inclination of 60°). We find that the H -band limit restricts the accretion rate to be $\dot{M} \lesssim 10^{14} \text{ g/s}$, largely independent of R_{out} . The submillimetre 3σ limit, on the other hand, restricts the outer radius to be $R_{out} \lesssim 10^{14} \text{ cm}$ or 7 AU. This outer radius is essentially independent of the accretion rate since the emission in the submillimetre is dominated by X-ray irradiation. Fig. 3 shows the predicted disc emission for a range of outer disc radii, and the maximum allowed value of the accretion rate, $\dot{M} \sim 10^{14} \text{ g/s}$. For the kinematic age of the pulsar, 0.5 Myrs, and the derived mass accretion limit, we can estimate the accretion rate $\dot{M}(t_0)$ during the initial time $t_0 \sim 1.5 \times 10^{-5} R_{d,7}^{1/2}(t_0) \text{ yr}$ (Menou et al. 2001; $R_{d,7}$ is the initial disc radius in units of 10^7 cm) before the power law decay begins (Cannizzo, Lee & Goodman 1990), and hence the initial disc mass $M(t_0) \sim \dot{M}(t_0)t_0 \sim 7 \times 10^{-5} M_\odot$. This upper limit for the initial disc mass is only a very small fraction of the overall fallback mass discussed to be in the range of $\sim 0.001 M_\odot$ to $0.1 M_\odot$ by Lin et al. (1991) and Chevalier (1989).

4.3 Looking at the past

As noted above and shown in Fig. 1, the projected trajectory of RX J1856.5–3754 crossed a CrA molecular cloud fragment roughly 3000 years ago. The current distance estimates for the CrA cloud ($\approx 130 \text{ pc}$; Neuhäuser & Forbrich 2008) and RX J1856.5–3754 ($167_{-15}^{+18} \text{ pc}$; preliminary distance by Kaplan et al. (2007) or $117 \pm 12 \text{ pc}$ by Walter & Lattimer (2002)) are close enough to each other to speculate about a possible encounter between the neutron star and the cloud fragment. Chini et al. (2003) investigated the R Corona Australis molecular cloud in detail by submillimetre contin-

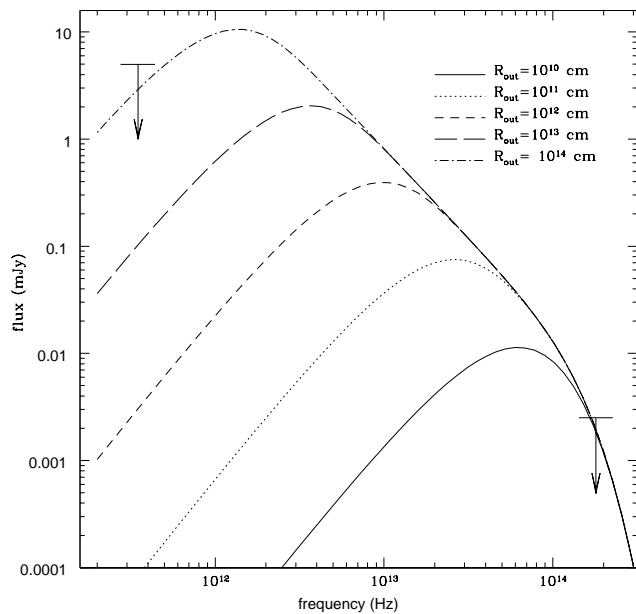


Figure 3. The predicted flux density for an optically thick, gaseous disc around RX J1856. The mass accretion is set to $\dot{M} = 10^{14} \text{ g s}^{-1}$ (maximum allowed value by the IR limit), and the different curves show the emission for a range of outer disc radii allowed by the sub-mm limit. Plotted are also the flux density limits from our APEX submillimetre observations and the H-band.

uum and line observations. Unfortunately, their map does not cover the cloud fragment west of RX J1856. For the cloud cores that they investigated in the extended eastern region, they derived densities on the order of $5 \times 10^{-21} \text{ g cm}^{-3}$ to $3 \times 10^{-17} \text{ g cm}^{-3}$. These are a factor 10^3 to 10^6 larger than what is usually assumed for the ISM. If RX J1856 crossed such a high density patch, this could have affected first a possible surrounding fallback disc, destroying it (Phillips & Chandler 1994) and second, it could have enabled the neutron star to accrete at higher rates from the ISM. The extended emission seen in the IRAS image unfortunately only allows us a crude estimation of a lower density limit in the fragment: We consider the IRAS/IRIS $100 \mu\text{m}$ emission in box 1 centered at the fragment in comparison to the emission in a box 2 of the same size, but centered around an area devoid of enhanced IRAS emission (see Fig. 1), that supposedly represents an average density value for the diffuse interstellar medium. By working with the flux density ratio we can ignore the problems involved in de-convolving the extended emission from the instrumental response. The flux density ratio, translating into a column density ratio, is 2.6. The distance to the cloud/fragment is at least 130 pc and we take this as the *minimum* distance, d_2 , along which the column density, $N_2 = n_2 \times d_2$, is derived from the number density, n_2 , in box 2. The angular extent of the fragment along the direction of the proper motion of RX J1856 is around $18'$, corresponding to $\approx 1 \text{ pc}$ at a distance of 130 pc. We assume the same extent of the fragment along the line of sight, $d_1 \approx 1 \text{ pc}$; the column density, N_1 , in box 1 is $N_1 = n_1 \times d_1 + n_2 \times d_2$. Therefore, the ratio of the number density in the fragment to the number density of the diffuse ISM is at least 200, $n_1/n_2 \geq 200$. Accord-

ing to Phillips & Chandler (1994), at a number density of $200 \text{ particles cm}^{-3}$, the smallest dust grains ($< 0.1 \mu\text{m}$) in a fallback disc can be removed within 3600 years, assuming a neutron star velocity of 100 km s^{-1} as estimated for RX J1856 (e.g., van Kerkwijk & Kulkarni 2001). Larger disc particles, however, would still survive and can be detected in principle in the submillimetre wavelength regime. The fact that we do not detect them in our APEX observation could mean that RX J1856 passed a patch of much higher ISM density, destroying its potential fallback disc. However, since the data about a possible encounter between the cloud fragment and RX J1856 is currently insufficient (unknown 3D motion of the neutron star and distance of the fragment), it is also possible that there never was a circumstellar disc with a dust mass higher than few earth masses.

Overall, the above speculations show that a better knowledge of the past neighbourhood of RX J1856 is desirable. This can be obtained in principle by further millimeter continuum or molecular line observations.

5 CONCLUSIONS

We investigated RX J1856.5–3754 for $870 \mu\text{m}$ continuum emission which would be indicative of a cold dusty disc around the neutron star. The derived deep flux density limit translates into a dust mass limit of few earth masses. Applying the irradiated (gas-rich) accretion disc model by Perna et al. (2000), together with further observational constraints, we obtained a mass accretion limit of $\dot{M} \lesssim 10^{14} \text{ g s}^{-1}$, and a constraint on the outer disc radius, R_{out} , to be smaller than 10^{14} cm or 7 AU. Looking at the projected proper motion of RX J1856.5–3754, we note that the neutron star might have passed a dense fragment of the CrA molecular cloud a few thousand years ago which could have affected a potential circumstellar disc, as well as have enabled a brief history of accretion from the ISM.

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